AD620 214

AMRA MS 65-05

AMRA MS 65-05

MATERIALS ENGINEERING FOR COLD REGIONS AND THE BRITTLE FRACTURE PROBLEM

MONOGRAPH SERIES

by

MURRAY M. JACOBSON

AUGUST 1965

MATERIALS ENGINEERING DIVISION
U. S. ARMY MATERIALS RESEARCH AGENCY
WATERTOWN, MASSACHUSETTS 02172

MATERIALS ENGINEERING FOR COLD REGIONS AND THE BRITTLE FRACTURE PROBLEM

Murray M. Jacobson

Materials Engineering Division

Presented at

15th Alaskan Science Conference
American Association for the Advancement of Science
College, Alaska
31 August - 4 September 1964

MATERIALS ENGINEERING FOR COLD REGIONS AND THE BRITTLE FRACTURE PROBLEM

Murray M. Jacobson
U. S. Army Materials Research Agency
Watertown, Massachusetts

INTRODUCTION

The U. S. Army has a long historical interest in the effect of cold environments on materials used in military equipment. During World War II the Army's low temperature materiel and materials problems were pointed up in the winter tests of 1942-43 at Camp Shiloh in Northern Manitoba. Military equipment problems associated with cold regions were further underlined as a result of the very recent U. S. Army winter exercises "Great Bear" and "Timberline." The requirements for materials able to withstand unusually cold environments are still further emphasized by the inclusion of a climatic category with a lower limit air temperature of -80° F in U. S. Army Regulation AR 705-15, Cl dated 14 October 1963 ("Operation of Materiel Under Extreme Conditions of Environment"). Even without the problem of ambient climatic conditions, the advent of Army missiles and rockets powered by cryogenic fuels imposes requirements for materials which retain good mechanical properties down as low as -423° F, the temperature of liquid hydrogen.

When subjected to low temperatures, most engineering materials show a substantial loss of the useful structural properties possessed at ordinary temperatures. Although wood, ceramics and glass are virtually unaffected by extreme cold, the more important classes of engineering materials, namely metals, rubber and plastics, are indeed subject to mechanical failure. Cold regions also impose lubricant problems. Rubber materials generally lose flexibility at low temperatures and become hard and brittle, although many of the newer synthetic elastomers retain flexibility down to extremely low temperatures. Most plastics harden and embrittle, and will fracture on shock loading or impact at low temperatures. Most structural metals, particularly the steels, are subject to catastrophic brittle failure in cold environments. Since metals constitute the largest tonnage usage

PRESENTED AT
15TH ALASKAN SCIENCE CONFERENCE, AAAS
COLLEGE, ALASKA AUG 31-SEPT 4, 1964

of engineering materials by the military, discussion in this paper will be addressed primarily to that class of materials. Rubber, plastics and lubricants, however, will be discussed briefly first.

RUBBER

Cold regions adversely affect the serviceability of rubber components of military equipment, such as tires, inner tubes, cable, hose, bushings, seals, etc. The low temperature effects of greatest concern include changes in flexibility, changes in compression-set characteristics and the development of brittleness .

The distinct changes that may occur in rubber at low temperatures can be classified as: simple temperature effects (visco-elastic effects); first-order transitions (crystallization); second-order transitions (vitrification); and effects associated with plasticizers. Simple temperature effects are manifested by loss of resilience, increase in modulus and increase in hardness. First-order transitions are time dependent and may require periods ranging from hours to months; they are accompanied by changes in hardness, volume and coefficient of thermal expansion, in addition to increased stiffness. Second-order transitions are exhibited by all elastomers and occur quite rapidly within a narrow temperature range. Elastomeric materials ordinarily become unserviceable due to simple temperature effects well above the second-order transition temperatures. When rubber compositions are highly loaded with certain plasticizers, time effects not necessarily associated with crystallization may be evident. Low temperature flexibility may be improved by the addition of selected plasticizers; however, this is usually done at the sacrifice of other properties, such as tear and abrasion resistance, and bondability.

Although rubbers that retain rubber-like properties at very low temperatures (see Table I) are available for use in cold regions, continued research is needed on new elastomers having broad versatility. Current low temperature rubbers, for example, do not possess adequate chemical resistance for use in hoses that must handle fuels, hydrocarbon oils, hydraulic fluids and lubricants. Rubber fuel hoses stiffen and break at low temperatures because the fluids extract compounds from the rubber that impart the original low temperature qualities. A fruitful

TABLE I

RELATIVE LOW TEMPERATURE CHARACTERISTICS OF SOME ELASTOMERS

Type	Typical Brittleness Temperature (° F)	Temperature Range for Rapid Stiffening (° F)
Neoprene	-40	+10 to -20
Butyl	-50	0 to -20
Natural Rubber	-65	-20 to -50
Styrene - Butadiene	-75	-50 to -60
Polyurethanes	below -90	-10 to -30
Silicones (General Purpose)	-90	-65
Fluorosilicones	-90	-75
Silicones (Extreme Low Temp.)	- 150	-105

area of further research probably lies in synthesis of elastomers based on modified polyurethanes and fluorinated silicones.

PLASTICS

The strength of plastics increases as temperature decreases. However, the ductility of nearly all plastics decreases in cold environments. Many classes of plastics can be used successfully at temperatures down to -40° F provided they are not subject to shock loading. Polyethylene, a thermoplastic polymer, remains tough at temperatures as low as -100° F and has considerable utility for military use. At extremely low temperatures only the fluorocarbon plastics, e. g. polytetrafluoroethylene (Teflon) and polychlorotrifluoroethylene (Kel-F), retain useful ductility. The fluorocarbon plastics possess unusually good chemical inertness and other advantages, but they are costly.

Further study is needed on the fundamental factors affecting the mechanical behavior of plastics and on developing a broader range of plastics for use in cold regions. There is also need for development of high strength structural adhesives with sufficient elasticity and bond strengths for use in fabricating composite structural materials for service in cold regions.

LUBRICANTS

In cold regions serious vehicle lubrication problems are frequently encountered, although undoubtedly many difficulties can be avoided by strict adherence to lubrication orders and engine maintenance procedures. Commercially available engine lubricants and gear lubricants, covered by military specifications, are useful down to at least -65° F. Available instrument greases are useful down to at least -100° F. Solid film lubricants based on molybdenum sulfide or polytetrafluoroethylene offer excellent serviceability in certain applications and can provide lubricity down to cryogenic temperatures. Although tremendous advances have been made since World War II in development of improved low temperature lubricants, continuing

research is required, for example, on low temperature engine lubricants. Some low temperature synthetic engine lubricants, having excellent viscosity and lubricity characteristics, require further development because they may not possess good compatibility with seals and bearing materials.

BRITTLE FRACTURE OF METALS

Sudden and frequently catastrophic metal fractures in which low temperature environment has been a contributing factor have occurred in large cannon, armored structures, rifles, mortars and bridging equipment, and more recently, in motor cases, hydraulic accumulator components and support hardware of missile systems.

Early records of cannon failures showed that most gun ruptures occurred during the winter months, or in other seasons during the first round of the day when the weapon was coldest. Metallurgical factors were not fully understood in those early days, and failures were sometimes diagnosed as "overpressure," "barrel obstruction" or "premature shell explosion." The Army first recognized the important influence of low temperatures on metallurgical behavior as a result of research on notch bar impact tests on steel conducted after World War I at the U. S. Army Materials Research Agency (then Watertown Arsenal Laboratories). Army research on behavior of materials at low temperatures and the recognition of special requirements of steel, particularly for guns and armor, have accelerated since the beginning of World War II.

It is now recognized that the significant effect of cold environments on the mechanical behavior of metals is the tendency to induce brittle failure. It is also acknowledged that metals may fracture suddenly in a brittle manner even in ordinary temperature environments. Thus, to fully understand the factors affecting the behavior of engineering metals at low temperatures, it is essential to rationalize the more general phenomenon of brittle behavior, which is a subject of considerable scientific interest and has wide practical implications. Basic aspects of this complex problem are not completely understood, although progress is being made toward developing criteria for evaluating materials in terms of their tendencies to resist brittle failure. The remainder of this paper will be devoted to describing some

aspects of the brittle fracture problem, such as the concept of transition temperature, the influence of notch defects and evaluation of fracture toughness, with the purpose of conveying some appreciation of these concepts to those whose principal interests may not lie directly in the areas of metallurgy or materials engineering. A comprehensive presentation of the U. S. Army Materials Research Agency's views and current state of knowledge on materials behavior with respect to brittle fracture are contained in a recent technical monograph (4).

Transition behavior and crystallographic structure. With temperature decrease metallic materials actually become stronger, as reflected in higher measured yield strengths and ultimate tensile strengths. However, metals are also likely to develop lowered resistance to impact or shock loading and become dangerously brittle. Toughness or lack of it then becomes an overriding consideration, and an important governing factor is the so-called transition temperature range. This is the temperature below which a material behaves in a brittle manner, the mode of failure being primarily by a cleavage mechanism, and above which it behaves in a ductile manner, the mode of failure being predominantly by a shear mechanism. The transition temperature depends on a variety of metallurgical and mechanical factors; however, some qualified generalities can be made regarding the proneness of various classes of metals to ductile-brittle behavior. Metals with the face-centered cubic crystallographic structure (e. g., the austenitic stainless steels, aluminum, copper, nickel, lead, silver, gold and the platinum group metals) do not exhibit brittleness at any temperature (except when a second metallurgical phase is present). The body-centered cubic metals (e. g., most of the structural steel alloys and metals such as columbium, molybdenum, tantalum, tungsten, vanadium and chromium) display abrupt ductile-to-brittle transitions. Metals having the hexagonal close-packed structure (e. g., titanium, zirconium, magnesium, beryllium, cobalt, zinc and cadmium) characteristically exhibit low temperature behavior similar to that of the body-centered cubic metals. An important exception is that some high-purity titanium alloys display increased strength at low temperatures with little sacrifice in ductility.

Notch defects. The fact that the transition temperature of a metal is below the service or environmental temperature provides no guarantee against brittle failure. The presence of notch-type defects can exert a profound influence on susceptibility to low temperature failure of structural parts. The effects of

temperature and of notches are additive, in that the presence of notches can raise the transition temperature, and a wide variety of notch-type defects as well as geometry changes can initiate brittle fractures. These include keyways, holes, sharp fillets, threads, scratches, nicks, machining marks, corrosion pits, inclusions, tiny cracks, discontinuities, etc. The defect or notch serves to concentrate stresses so that, even though the nominal stress may be low, the local stress at the discontinuity is quite high. The high local stress of the notch initiates a crack, which under the proper conditions of temperature, metallurgical structure and section geometry can propagate rapidly, frequently at extremely high rates. Figure 1 illustrates schematically the effect of temperature on the notch strength of steel. Note that the notch strength can decrease to a very low percentage of the inherent tensile strength.

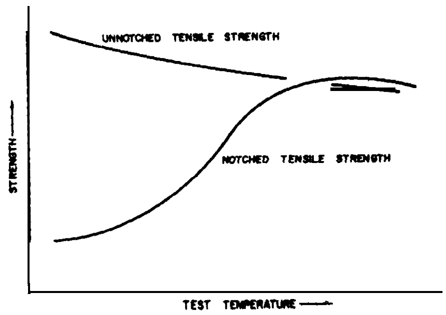

Figure I. EFFECT OF TEMPERATURE OR TENSILE STRENGTH

Strain rate effects under conditions of complex stress states cause a marked increase in transition temperature. It may be of interest to describe how a biaxial stress results from the presence of a notch, for example a circumferential notch introduced in a simple tension bar. The metal at the bottom of the notch is under much higher longitudinal stress than the adjacent material because of the stress concentration factor, and due to Poisson's ratio it tends to contract strongly in the transverse direction. The surrounding material is under lower longitudinal stress and thus contracts much less transversely. Transverse contraction of the material immediately adjacent to the base of the notch is therefore restrained by the surrounding metal. Consequently, a transverse tensile stress is introduced on the material at the

base of the notch. Thus a biaxial stress exists at the base of the notch even though the external load is uniaxial. Biaxial tension tends to raise the transition temperature markedly and increase brittle behavior. Both effects, the effect of the notch in introducing biaxial stress and its effect on increasing strain rate, are in the same direction, with the result that the transition range in a notched part or test specimen is considerably higher than for an unnotched part. If in addition to a notch there is a high rate of loading by shock or impact, the increase in strain rate can be enormous. The strain rate in the Charpy notched bar impact test (which will be discussed later) is of the order of 1000 in/in/sec, which is ten million times greater than the strain rate in the usual static tension test. This tremendous difference in strain rate drastically increases the transition temperature of the material, and on it is superimposed the embrittling effect of the notch. Since notches and shock loads are often encountered in service, it is not surprising that a material that is tough in a static tensile test, even at low temperatures, may fail brittlely in service.

In addition to the presence of the notch itself, the notch acuity and the critical length of cracks which propagate from notches are very important. The importance of notch sharpness on the strength of sheet steels can be illustrated by reference to Figures 2 and 3. The notch radius of the sheet tensile specimen shown in Figure 2 is 0.001 inch maximum, which provides a stress concentration factor (Kt) of about 18. If in a series of tests this radius is varied from infinity (an unnotched specimen) down to 0. 001 inch, using specimens from two steels of the same strength level, one known to be notch tough and the other to be notch brittle, test data are obtained as typified in Figure 3. The presence of a dull notch (K_t from 1 to 6) actually strengthens both tough and brittle material. However, as the notch becomes increasingly sharper, the strength of the tough material becomes only moderately impaired, while the strength of the brittle material is severely lowered. For cold environments it is obvious that the tough material is to be preferred over the brittle one.

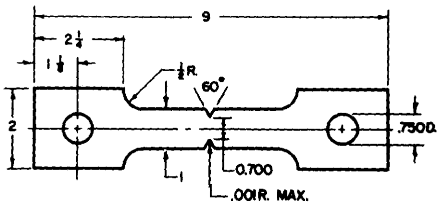

Figure 2. SHEET TENSILE SPECIMEN

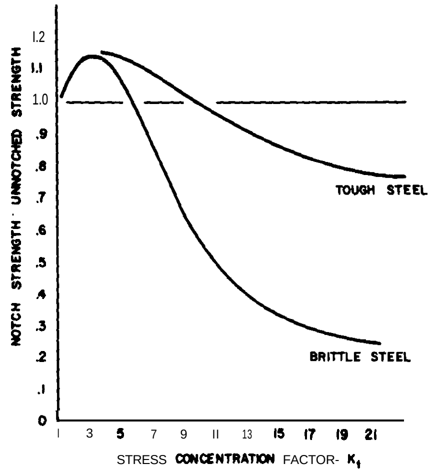

Figure 3. EFFECT OF NOTCH ON TENSILE STRENGTH

Metallurgical factors. The primary differences between tough and brittle steels derive from their microstructures. The microstructures in turn are dependent on composition, heat treatment and other processing conditions. This embraces the chemical, mechanical and thermal environments encountered during manufacture and fabrication. The inherent toughness of a material depends not only on the matrix, but also on the morphology and distribution of the phases which coexist with the matrix. In the absence of second phases, the general behavior of a metallic matrix is usually indicated by its crystallography, as pointed out earlier. Metals of the face-centered cubic system sustain only a gradual loss of toughness through a range of decreasing temperatures. Body-centered cubic metals undergo a transition from ductile to brittle behavior with decreasing temperature. Hexagonal close-packed metals generally behave similarly to the body-centered cubic metals. The exceptions to these generalizations are attributed to the degree of purity. High purity benefits the resistance to fracture by lowering, but not eliminating, the actual transition from ductile to brittle behavior. Additional phases in any of these three types of matrices exert an influence on the toughness. Thus, the inherent toughness of metallic materials is dependent on many factors.

Extensive data have been published in the literature on the effects of composition, heat treatment and work on literally

hundreds of different steels. A few steel compositional trends may be noted. In general, the so- called interstitial elements (carbon, oxygen, nitrogen and hydrogen) embrittle iron-base alloys more severely than the substitutional alloy elements. Nickel is one of the elements which exhibits the strongest effect in reducing the transition temperature behavior of low carbon alloy steels. The dramatic influence of nickel content is illustrated by the curves in Figure 4. It may be added that alloys containing above 8. 5% nickel are suitable even for temperatures down to -320° F.

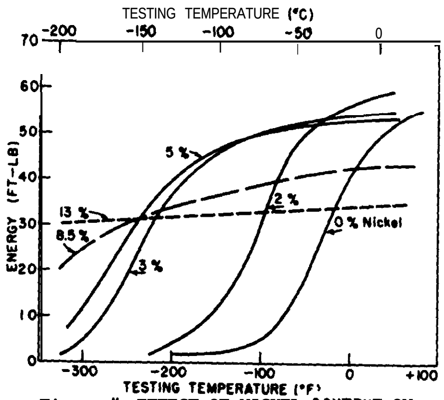

Figure 4. EFFECT OF NICKEL CONTENT ON TRANSITION BEHAVIOR OF A LOW CARBON STEEL (SAE HANDBOOK 1956)

Steels of greatest current interest to the Army are those which can be processed into sheet with engineering yield strengths well above 200, 000 psi. Steels of this type, being considered, for example, in missile applications where good low temperature toughness is required, include the 18% maraging steels, the low alloy medium carbon group (such as 4340 grade) and the austenitic stainless steels (such as Type 301).

Because of the high strength-density ratios that can be achieved with certain titanium alloys, this class of material also has considerable potential at low temperatures. One of the most promising alloys is titanium-5% aluminum-2% tin alloy having a so-called alpha hexagonal close-packed structure, which with adequate control of impurities, displays excellent high strength accompanied by good toughness and ductility even down to cryogenic temperatures.

Evaluating brittle fracture tendencies. Although a number of tests have been used for assessing brittle behavior of metals (such as the Izod Test, Explosion-Bulge Test, Schnadt Impact Test and many others), the most commonly used test method for determining transition temperatures and evaluating the toughness of metals is the V-notch Charpy impact test. A comparison of the low temperature behavior of different materials can also be made using notched standard round tensile specimens; however, the impact test is more widely used because of its greater simplicity.

The U. S. Army Materials Research Agency has had an identification with notch testing of steel at low temperatures which dates back several decades. Although today much remains to be learned regarding the fundamental significance of the test, use of the V-notch Charpy impact test has proven effective as a control test in specifications for materials intended for armor plates, gun tubes, breech blocks and other military items.

The Charpy impact test consists of placing a suitable notched specimen, supported on both ends, as a beam, and applying a single pendulum blow behind the notch. The energy of the pendulum is known before impact, and by determining the energy in the pendulum after impact, the energy used to break the specimen can be determined. The standard Charpy specimen is shown in Figure 5.

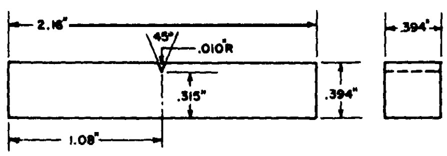

Figure 5. STANDARD V-NOTCH CHARPY SPECIMEN

Results obtained by carrying out a series of impact tests over a range of temperatures are illustrated in Figure 6. Note that the energy decreases from a high level at the upper temperatures to a low value at low temperatures. Examination of the broken specimens shows that at temperatures where the material is tough, there has been considerable plastic deformation in the vicinity of the fracture, and the energy for this plastic deformation represents a considerable portion of the energy absorbed by the pendulum. At low temperatures, below the transition, there is little deformation in the vicinity of the fracture and low energy absorption.

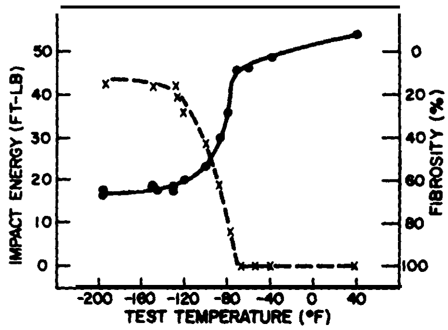

Figure 6. IMPACT TEST RESULTS

In addition to measuring the energy absorption, one can also obtain information from the appearance of the fracture surface. At low temperatures the fracture is crystalline, whereas at high temperatures the surface may appear fibrous. The percent crystallinity may be plotted versus testing temperature, and the decrease in energy absorption parallels the increase in crystallinity. For use in defining the transition temperature, either the percent crystallinity (as determined by examination of the fractured surface) or the energy absorption can be used.

The U. S. Army has been instrumental in sponsoring the adoption by industry of the Charpy impact test, through the existence of an impact requirement in specifications. While the quantitative value cannot be used directly in design, there is sufficient background to demonstrate its usefulness in predicting service behavior.

Despite its usefulness in assessing a wide variety of engineering metals, the Charpy test does have limitations. First, there is the size limitation imposed by the sheet materials coming into greater use. Another restriction is that the Charpy test becomes less sensitive for materials with strengths above 200, 000 psi. High strength materials have inherently low toughness; consequently, a comparison must be made between relatively small numbers.

In the past few years, considerable interest has centered on study of fracture using notched flat tensile specimens. There are

several reasons for this. Since many new military components are made from thin wall or sheet materials, standard size Charpy impact specimens or round notch tensile specimens cannot be used, and some type of sheet specimen must be adopted. Concurrent with this increased requirement for sheet materials has been the development of the concepts of fracture mechanics which allow study of the crack propagation component of the fracture process and which entail the use of notched precracked sheet tensile specimens. The fracture mechanics approach holds considerable promise because it should provide a tool for the design engineer to more precisely predict the relative sensitivity of candidate materials to brittle failure. It also allows calculation of the maximum tolerable flaw size in components of engineering structures. The indices of fracture toughness determined by fracture mechanics are the parameter G_c, the critical crack extension force or the elastic strain energy release rate necessary to maintain a fast running fracture, and the parameter K_c, the critical stress intensity or crack toughness index.

Special specimen geometries and special measurements are required to determine these parameters. Suffice to point out that edge notched or center notched sheet specimens are employed, wherein the actual crack is extremely sharp, resembling a natural crack, and is induced by controlled fatiguing in a tension-**tension fatigue machine. The procedures and calculations are described in the findings of the American Society for Testing and Materials (ASTM) Committee on Fracture Testing, which issued its first report in 1960 (2) and its fifth report in March 1964 (3).**

To obtain valid measurements for the fracture toughness indices, material must fracture before it undergoes general yielding, which means that the fracture mechanics parameters, although suitable for very brittle materials, are not equally reliable for the newer <u>tougher</u> high strength steels. For the tougher materials, the analysis of the elastic stresses requires modification to take into account the plastic action at the advancing crack tip. The ASTM consequently is not quite ready to prescribe an official recommended practice for fracture toughness testing until the fracture phenomenon is more thoroughly understood. For example, to obtain the K_c parameter it is essential to measure slow crack growth prior to sudden fracture more accurately than by presently employed techniques (such as ink-staining or by estimating the shear fraction of the fractured surface). A phase of current research on fracture mechanisms at the U. S. Army Materials Research Agency includes study of this problem, and an improved method for measuring slow crack

growth has been proposed which involves determining the electrical potential difference between two points on either side of a notch as a function of crack growth (1).

Design philosophies regarding defects. Good notch toughness is essential for engineering materials for critical components intended for low temperature service. Steels, particularly the high strength sheet alloys, have varying degrees of notch toughness, and defects capable of triggering brittle fracture can be present as metallurgical defects or can be initiated during either fabrication or service. From a qualitative design standpoint, two general philosophies can be adopted regarding defects and brittle fracture susceptibility. One is to require that all components manufactured from high strength materials be constructed free from defects. The other view is that since it is virtually impossible to manufacture defect-free components from high strength materials, then high notch toughness in the material should be a prerequisite to its use in military structures. In theory, each philosophy is sound. The “no defect” philosophy assumes that solutions can be found for several very difficult production, fabrication and inspection problems. Since such problems remain to be fully solved on a practical basis, the second design philosophy is considered a much more rational one to follow within the present state of the art. Admittedly, a problem exists in specifying a test to insure adequate notch toughness so that many small defects can be tolerated in a structure without the occurrence of brittle fracture. As discussed earlier, an approach to this problem is being pursued using fracture mechanics concepts. Design based on the assurance of at least some degree of notch toughness is far better than design based on the assumption that a structure is completely devoid of defects.

SUMMARY

Most rubber and plastics materials lose flexibility and become dangerously embrittled in cold regions, although certain classes of these nonmetallic engineering materials are available which are serviceable even at extremely low temperatures.

Low temperature mechanical behavior of a metal can be correlated with its intrinsic crystallographic structure. In addition to crystal structure, factors such as chemical composition,

purity, heat treatment and processing variables influence behavior of metallic materials at low temperatures.

In cold environment, most engineering metals actually become stronger, but they lose ductility and become dangerously brittle. Thus, the major problem at low temperatures is brittle fracture. The presence of notch defects, particularly in the case of high strength alloys, plays a predominant role in contributing to sudden brittle fracture. The V-notch Charpy impact test has been used effectively as an inspection criterion for screening brittle materials for armor, cannon and other military applications. Additional research is required, however, to establish toughness criteria for thin-walled structures and for the newer ultra-high strength sheet materials. Parameters based on rational fracture mechanics concepts, although not yet adequate for specification standards, offer a promising design procedure for prevention of brittle behavior. With these tools, it should eventually be possible to select materials which are adequate for a critical structural application in a given climatic environment, or to specify a minimum acceptable value of toughness for marginal material.

REFERENCES

1. Anctil, A. A., E. B. Kula and E. DiCesare. Electrical potential technique for determining slow crack growth. ASTM Preprint No. 78 c, also AMRA TR 63-27, U. S. Army Materials Research Agency, Watertown, Mass. , 1963.

2. Special American Society for Testing and Materials Committee. Fracture testing of high strength sheet materials. ASTM Bull. No. 243, pp. 29-40 (Part I) and No. 244, pp. 18-28 (Part II), 1960.

3. Special ASTM Committee. Progress in measuring fracture toughness and using fracture mechanics. Materials Research and Standards, Vol. 4, No. 3, pp. 107-119, 1964.

4. U. S. Army Materials Research Agency. Fracture of structural metals. Monograph Series MS-48, 1962.